Constraints on the pairing properties of main sequence stars from observations of white dwarfs in binary systems.

Lilia Ferrario
Mathematical Sciences Institute, The Australian National University, Canberra, ACT 0200, Australia

ABSTRACT

Observations of main sequence stars conducted over the last several decades have clearly shown that something like 50 per cent of stars of spectral types G and F occur in multiple systems. For earlier spectral types, the incidence of multiplicity is even higher. Thus, a volume limited sample of white dwarfs should reflect the percentage of binarity observed in stars of F to late B spectral types, which are their Main Sequence progenitors. However, a study of the local volume limited sample of white dwarfs (20 pc from the Sun) conducted by Holberg has shown that a white dwarf has a probability of only ~ 32 per cent of occurring in a binary system, in stark contrast to the observations of multiplicity of Main Sequence stars. Others studies have also led to the same conclusion.

In this paper, we argue that the "hidden" white dwarfs are either in double white dwarf systems or in Sirius-like systems. We also show that the white dwarf progenitors of the SDSS white dwarf - M dwarf wide binaries are distributed according to Salpeter's IMF. However, they cannot be paired with secondary stars which are also drawn from this IMF, since such a pairing would produce a percentage of white dwarf-M dwarfs systems that is several times larger than observed.

Key words: White dwarfs, Binaries: general, stars: formation, stars: low-mass.

1 INTRODUCTION

White dwarf-M dwarf pairs are commonly discovered in any surveys of white dwarfs. The observed pairs fall into three basic groups. In the first group (group A), the more massive star evolves into a white dwarf without ever interacting with its companion. These are the so-called wide binaries. In the second group (group B), the binary stars have smaller initial separations and will eventually evolve through a common envelope (CE) phase as the more massive star becomes a white dwarf. These are the post common envelope pre-Cataclysmic Variable binaries (Pre CVs). The third group (group C) consists of pairs that have already evolved through a CE phase and are currently seen as close interacting binary systems where there is evidence of mass transfer (current or in the past). Thus, the M dwarfs in these systems are either filling or close to filling their Roche lobes. These are the Cataclysmic Variable (CVs) stars.

Studies aimed at determining the observed distribution $f_{\rm obs}(q)$ of mass ratios $q = \dfrac{M_s}{M_p} < 1$, where M_p is the mass of the primary star and M_s is the mass of its less massive companion, are generally limited to establishing the nature of the distribution for $q \geqslant 0.1$ when the luminosity of the secondary star is not swamped by that of the primary. On the other hand, insights into the behaviour of $f_{\rm obs}(q)$ at

low values of q can be more easily obtained from studies of the pairing of white dwarfs with main sequence companions belonging to group A and through simple assumptions on the initial-final mass relationship for white dwarfs.

In this paper, we analyse the pairing properties of white dwarf - Main Sequence binaries using as constraints the white dwarfs - M dwarf sample from the SDSS belonging to group A (wide binaries), the Holberg (2009) percentage of observed white dwarf binaries in the 20 pc local sample and observations of the mass ratio distribution of binary Main Sequence stars. We then present some conclusions on the pairing properties of Main Sequence low to intermediate mass stars, which are the progenitors of the currently observed white dwarfs, and link them to possible star formation scenarios.

2 THE OBSERVATIONAL BASIS

2.1 Mass ratio distribution of binary main sequence stars

Early studies of binary systems pointed to a bi-modal distribution of $f_{\rm obs}(q)$ (e.g. Trimble (1974)): a population $f_{\rm obs}(q)$ which increases with increasing q and reaches a maximum near $q = 1$ thus showing a preference for stars of similar

masses (twins), and a second population $f_{obs}(q)$ which initially rises towards lower q, reaches a maximum at $q \sim 0.2$ and then decreases. More recent studies using F7 to K-type primary stars by Halbwachs et al. (2003) have shown that $f_{obs}(q)$ has a very broad peak at $q \sim 0.2 - 0.7$ (perhaps with sub-structure) and a sharp peak for $q \gtrsim 0.8$ (twins). Interestingly, these authors claim that the $f(q)$ relationship is "scale-free" for stars in the three different sub-groups that comprised their F7-K star sample.

Kiminki & Kobulnicky (2012) conducted a statistical analysis of massive binaries in the Cygnus OB2 association using radial velocity data for 114 B3–O5 primary stars. They found a mass ratio distribution $f_{obs}(q) \propto q^{\alpha}$, with $\alpha = 0.1 \pm 0.5$, which is consistent with their previous work (Kobulnicky & Fryer 2007). This is also in agreement with the observations of Kouwenhoven et al. (2005), who find that A and late B-type stars in the Scorpius OB2 association have a mass ratio distribution with $\alpha = -0.33$, and with the studies of Shatsky & Tokovinin (2002), who also surveyed B-type stars in Scorpius OB2 for binarity and found α in the range -0.3 to -0.5. Studies of a sample of massive binaries in the Small Magellanic Cloud conducted by Pinsonneault & Stanek (2006) revealed that their primaries appear to have two populations of companions: a "twin" population with $q > 0.95$ comprising 45 per cent of binaries, and a population with $f_{obs}(q) \sim$ constant (i.e. $\alpha = 0$) comprising 55 per cent for their sample. On the other hand, Sana & Evans (2011) claim that there is no indication for a twin population in their Galactic O-star sample and that the mass-ratio distribution is essentially flat for $0.2 < q < 1.0$. The studies by Raghavan et al. (2012) on companions to solar-type stars indicate that the mass ratio distribution is flat for $\sim 0.2 \leqslant q \leqslant 0.95$.

Woitas et al. (2001) studied the masses and mass ratios of pre-Main Sequence stars. Interestingly, they also found that the distribution of mass ratios in T Tauri binaries is essentially flat for $q > 0.2$ and it has no correlation with the primary's mass or the stellar separation. They also found that there is no significant preference for $q \sim 1$ (twin component).

In summary, at the present time it appears that the $f(q)$ distribution is either flat or slightly raising toward $q \sim 0.1 - 0.3$ with or without a rise toward $q = 1$ (twin). Interestingly, these studies appear to agree for primaries ranging from solar to early O-type stars and even for young protostellar associations. However, none of these studies extends to low enough mass ratios to investigate the true incidence of binaries whose secondaries are M dwarfs.

2.2 Observations of white dwarf - main sequence star binaries

While an M-dwarf is easily hidden in the glare of an intermediate or high-mass star primary, such a low luminosity star should be more easily seen after its more massive companion has evolved into a compact star. Thus, insights into the behaviour of $f(q)$ at low q can potentially be obtained from studies of the pairing of white dwarfs with low-mass main sequence stars and by assuming an initial to final mass relationship for white dwarfs (e.g. Ferrario et al. (2005)).

A rather surprising result resides in the observed incidence of binarity among white dwarfs.

Farihi, Becklin & Zuckerman (2005) found that the stellar companion fraction of white dwarfs is 22 per cent, uncorrected for bias. Furthermore, they also found that most of the stellar companions to white dwarfs are low-mass M dwarf stars. Similarly, Holberg (2009) found that only 32 ± 8 per cent of the local white dwarf population has a companion of *any* type.

However, it is well known that the progenitors of the currently observed white dwarfs, which are Main Sequence stars in the mass range $\sim 1.2 - 8 M_{\odot}$, exhibit a percentage of binarity of at least 55 per cent at the low mass limit (F type stars), to 60 per cent or more toward the upper end of the mass range limit (late B type stars). Thus, there must be an additional ~ 30 per cent of as yet undiscovered white dwarfs lurking in some kind of binaries.

Interestingly, if one assumes that the majority of white dwarf-M dwarf binaries in the local sample has already been detected, since any M dwarf red excess would be clearly visible in the spectrum of a nearby white dwarf, then according to the percentages given by Holberg (2009), the incidence of this type of pairing could be *as low as* ~ 18 per cent, consistent with the findings of Farihi, Becklin & Zuckerman (2005). Considering that M-dwarfs are the most numerous stars in the Galaxy, the fact that they are somewhat rarely paired to white dwarfs, suggests that binary formation mechanisms tend to exclude them as companions of F to late B-type stars.

Another possibility that cannot be excluded a priori is that the local white dwarf binary population is not representative of the true Galactic population. If this is the case, our calculations, which use as constraint current observations of Galactic stellar multiplicity, will simply give predictions that would be applicable to a complete white dwarf binary sample.

We show in Fig. (1) the spectral distribution of M dwarfs found in wide binaries containing a white dwarf from the spectroscopic SDSS Data Release 6 (Rebassa–Mansergas 2010).

We note that the peak in the M dwarf secondary distribution is near M3.5 and that there is a very steep decline in the number of M dwarfs of spectral type later than M5. Interestingly, Farihi, Becklin & Zuckerman (2005) also find that the peak frequency in spectral type occurs around M3.5 for *both* field M dwarfs and M dwarf companions to white dwarfs (see their Figures 6 and 7). However, relatively to the peak, they find that there are $\sim 2 - 3$ times more L dwarfs and $\sim 4 - 5$ times more M6M9 dwarfs in the field than among companions. Thus, despite the excellent sensitivity in their survey to late-M dwarfs and early-L dwarfs very few of these low-mass companions were detected.

We note that the SDSS white dwarf - M dwarf binary data suffer from strong selection effects, since the SDSS is a magnitude-limited survey. Thus, one should expect that selection effects may become dominant at later spectral types (M5 to M9) if the white dwarf is more luminous than the M dwarf, or at early spectral type (M0 to M2), when the fainter white dwarfs may be hidden by the more luminous M dwarfs. Therefore, one may expect that even after introducing corrections for observational biases, the peak of the distribution would remain around M3.5. We shall use this peak as a constraint for our studies in section (4.2).

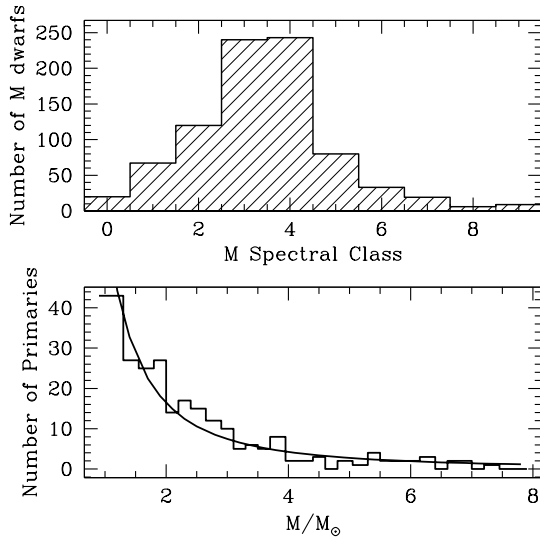An important piece of information that can be extracted

Figure 1. Top panel: Spectral class of M dwarf companions to white dwarfs in the wide binaries of Rebassa–Mansergas (2010). Bottom panel: Mass distribution of white dwarf progenitors after a final-to-initial mass relationship has been applied to the white dwarfs in the wide binaries in Rebassa–Mansergas (2010) (see text for details). Solid curve: best power law fit with index $\alpha = -1.95 \pm 0.14$.

from the data of Rebassa–Mansergas (2010) concerns the distribution of white dwarf masses - and thus of their Main Sequence progenitor masses. Since we need an initial-to-final mass function to obtain the masses of the WD progenitors, we have used the simple relation of Catalán et al. (2009). The histogram of the mass distribution that we have obtained is shown in the bottom panel of Fig. (1). This histogram shows that the number of WD progenitors drops very quickly with mass. We have found that the best power law fit to these data has an index $\alpha = -1.95 \pm 0.14$, consistent with the observational results of Chabrier (2003) who found a slope $\alpha = -2.3 \pm 0.3$ for single stars with $M > 1M_\odot$ in the galactic disk and young clusters.

In the next sections, we investigate pairing functions of main sequence stars. We will show that given the current observational constraints, there should be a sizeable fraction of WDs in Sirius-type systems and in double white dwarf binaries.

3 CALCULATIONS

In order to investigate the properties of white dwarfs in binaries, a number of systems was generated with primary masses distributed according to

$$\frac{dN}{d\log M_p} \propto M_p^{-0.95},$$

as indicated by the SDSS data (see previous section). The justification for this is that the distribution of primary masses should exactly reflect the distribution of their masses

at birth, since in these wide binaries the two stellar components have never come into contact and exchanged mass. One should also keep in mind that the mass range of the primaries is automatically restricted to $1.2 \lesssim M_p \lesssim 8M_\odot$ since the Galactic disk is not old enough for lower mass stars to have evolved to the white dwarf stage, while stars with $M \gtrsim 8M_\odot$ undergo supernova explosions and become neutron stars.

In our calculations, we have assumed that either (i) the masses of the two stars are both drawn from a mass distribution $f(M_s)$ with the constraint $M_s \leqslant M_p$ ($q \leqslant 1$) or (ii) the mass of the secondary star depends on the mass of the primary, or (iii) the binaries are generated according to a Salpeter's like distribution for the primary mass and with the secondary mass determined by a generating mass ratio distribution $f(q)$. Thus we have explored the following pairing cases

(i) A distribution for the mass of the secondaries given by

$$\frac{dN}{d\log M_s} \propto M_s^\rho \qquad (1)$$

where dN is the number of stars per unit volume per logarithmic mass interval $d\log M_s$ observed at time t. If $\rho = -1.35$, we have the Salpeter (1955) mass function.
(ii) A distribution for the mass of the secondaries given by

$$\frac{dN}{d\log M_s} \propto \begin{cases} \exp\left[\dfrac{-(\log M_s - \log M_c)}{2\sigma^2}\right] & \dfrac{M_s}{M_\odot} \leqslant 1, \\ M_s^\delta & 1 < \dfrac{M_s}{M_\odot} < 8. \end{cases} \quad (2)$$

This type of distribution was first suggested by Miller & Scalo (1979) and was more recently adopted by, e.g., Chabrier (2005) and Bochanski (2010). Here, $\log M_c$ and σ are the average mass and standard deviation, respectively, in $\log M_s$. In the distribution of Bochanski (2010) (used in this paper), $\log M_c = -0.745$ and $\sigma = 0.34$.
(iii) A Gaussian distribution where the mass of the secondary is proportional to the mass of the primary star M_p:

$$\frac{dN}{d\log M_s} \propto \exp\left[\frac{-(\log M_s - \log(kM_p))}{2\sigma^2}\right] \quad (3)$$

where k is the proportionality constant.
(iv) The mass of the secondary is determined by the mass ratio that is drawn from a generating mass ratio distribution $f(q)$ given by

$$f(q) \propto q^\beta \qquad 0 < q \leqslant 1 \quad (4)$$

We note that if τ_D is the age of the galactic disk, assumed to be 9.5 Gyr (e.g. Oswalt et al. (1996)), and $\tau_{\rm prewd}(M_i)$ is the nuclear burning evolutionary time of a star of initial mass M_i, then only those stars born at a time $0 \leqslant \tau \leqslant \tau_D - \tau_{\rm prewd}$ can currently be observed as white dwarfs of age $\tau_{\rm wd} = \tau_D - \tau_{\rm prewd} - \tau$. In our calculations, we have assumed that the Galactic star formation rate is is constant over the lifetime of the Galactic disc. To obtain an estimate of $\tau_{\rm prewd}(M_i)$, we have used the average stellar lifetimes given by Romano et al. (2005) based on the stellar evolution grids of Maeder & Meynet (1989).

The temperature of the white dwarf can then be calculated from its age $\tau_{\rm wd}$ and mass $M_{\rm wd}$ by interpolating
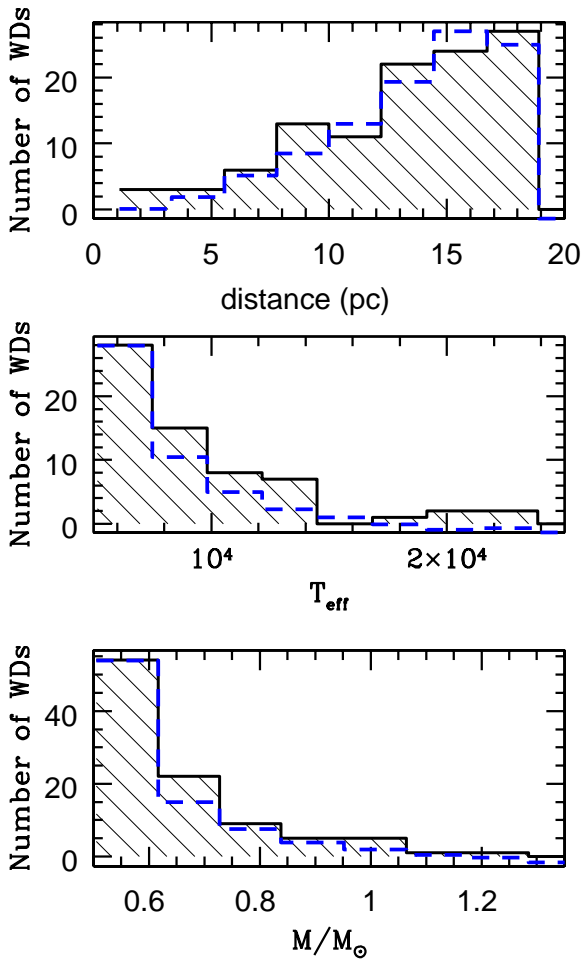
Figure 2. From top to bottom: Shaded histograms of distance, effective temperature and mass of the 20 pc sample of Holberg (2009). Dashed histograms: Synthetic white dwarf data.

the tables for evolutionary sequences of white dwarf atmospheres of Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011), and Bergeron (2011)[1].

Over the evolutionary time of the primary star and subsequent cooling as a white dwarf, some of the secondaries may also have had enough time to evolve and to be observed as white dwarfs at the present epoch. Thus, in addition to systems containing a white dwarf and a Main Sequence star, there will systems comprising of double white dwarfs. The mixture of the two will be dictated by the evolutionary timescales of the secondary star.

The white dwarf - Main Sequence binaries can then be further divided into systems with low luminosity M dwarf companions and systems with stars of earlier (K to late B) spectral type companions. The latter case yields "Sirius-type" systems. If the white dwarf and its main sequence star form a close system, then the white dwarf could be hidden in the glare of its main sequence companion (just like Sirius B). We note that observationally, it is estimated that about 45 per cent of Sirius-like systems are close or unresolved, with

the remainder being Close Proper Motion systems (Holberg 2012, private communication).

In order to check whether our calculations are consistent with the observational characteristics of the local sample of white dwarfs (Holberg 2009), we have plotted in Fig. (2) our white dwarf synthetic data for distance, effective temperature and mass overlapped to the 20 pc white dwarf sample of Holberg (2009). This figure shows that, considering the approximations outlined above for the stellar models, our synthetic population of non-interacting white dwarfs is consistent with observational results of isolated white dwarfs.

4 RESULTS AND DISCUSSION

4.1 Binary formation mechanisms

Given the complex nature of star formation, it is difficult to predict a priori the expected distribution of mass ratios in binary systems, since all stars, including binaries, form in clusters with a multitude of physical and dynamical factors coming into play.

Over the years, several routes leading to the formation of binaries have been identified. The main ones being (i) fission, (ii) capture, (iii) fragmentation. In fission, binaries arise from the slow contraction of a rotating gas cloud. Under the simplified assumption of incompressible, non-viscous fluids and of hydrostatic equilibrium, the contraction of a rapidly rotating object leads to a dumbbell-type configuration and to the formation of binaries with mass ratios close to unity. This mechanism was disproved by the numerical calculations of Durisen et al. (1986) who studied the stability of rotating, *compressible* gas clouds. They showed that the ejection of matter and the formation of a bar with trailing spiral structures can efficiently redistribute the angular momentum on a dynamical time scale avoiding the formation of a binary system.

The breakup of a fast rotating gas cloud while it is collapsing is referred to as "prompt fragmentation". This mechanism was first proposed by Hoyle (1953). Because of low compressional heating, the gas can cool radiatively and the contracting gas cloud is initially isothermal. As the cloud collapses, the density increases and the Jeans mass decreases causing fragmentation to take place. However, as contraction continues, the gas cloud's opacity increases causing its core to heat up. Fragmentation ends once a fragment's temperature, and thus its Jeans' mass, starts to increase. The critical value of opacity that halts contraction yields a minimum Jeans' mass value of about $0.01 M_\odot$. Early computational work on the formation of binary systems via fragmentation was conducted by Boss & Bodenheimer (1979). More recently, Clarke (1996) studied the scale-free fragmentation scenario and its observational implications.

Fragmentation of a protostellar disc, also called "disc fragmentation", occurs once the collapse of the cloud is over and protostellar objects have already formed. Bonnell & Bate (1994) proposed that fragmentation can occur via two mechanisms. One involves rotational instabilities in a protostellar core. The other invokes the formation of a rapidly rotating core which is unstable to axisymmetric perturbations. This core bounces into a ring which quickly fragments into several components.

[1] http://www.astro.umontreal.ca/~bergeron/CoolingModels

The capture mechanism implies that single stars have already formed and are still in a (dense) stellar cluster. Binaries are then created when one star captures another ("dynamical capture", see McDonald & Clarke (1993)). The required excess kinetic energy loss could occur via tidal dissipation, if the stars get sufficiently close to each other, or through dynamical encounter and transfer of energy to a third star. If capture occurs early on in the formation process and either one or both young stars are still surrounded by protostellar discs, then energy dissipation would effectively occur through discs-stars interaction ("star-disc capture", McDonald & Clarke (1995)).

Clearly, most of the above mechanisms are expected to play a role in a star forming region, although it is generally expected that cloud fragmentation may play a dominant role. This is certainly the picture that is emerging from the hydrodynamic simulations of star cluster formation, such as those conducted by Bate (2012), which can resolve masses down to a few Jupiter masses. Their calculations produce the Chabrier (2005) observed IMF and find that stellar multiplicity increases with the mass of the primary, in agreement with observations. Furthermore, they find a mass ratio distribution for solar-type and M-dwarf binaries which is roughly flat, again consistent with observations.

It is interesting to note that the flat $f_{obs}(q)$ distribution observed in protostellar objects seem to support the view that in most multiple systems in T Tauri associations the components' masses are mainly determined by the cloud's fragmentation process and not by the subsequent disc accretion processes (Woitas et al. 2001). This finding is corroborated by the numerical simulations of Bate (1997) who have shown that in the disc accretion stage following cloud fragmentation, the system's mass ratio would tend to approach unity, which is in disagreement with the observational work of Woitas et al. (2001). This result is very significant, since it indicates that binary characteristics are already determined as early as 1 million years after cloud fragmentation has begun.

We stress that what is observed (and usually fitted with power laws), is the "specific mass ratio" distribution $f_{obs}(q)$ which is obtained for a sample of stars with primaries in a given mass range (M_{p1} and M_{p2}, Kouwenhoven et al. (2009)). This is certainly the case if one studies the pairing properties of binaries whose primary stars are white dwarfs, since the progenitors of white dwarfs are main sequence stars with masses $1.2 \lesssim M_p \lesssim 8 M_{\odot}$. The observed mass ratio distribution is also usually confined to $q \gtrsim 0.1$ because observations are often incomplete below this value.

In what follows, we will consider the pairing possibilities listed in section (3) to see whether the existing observational constraints, comprising the SDSS white dwarf - M dwarf wide binaries, the local white dwarf binary sample, and the flatness of the observed mass ratio distribution, favour any of the aforementioned routes.

4.2 Results of calculations and comparison with observations

In the stellar capture scenario, single stars in dense, young clusters form binaries via "random pairing". This can be simulated if we draw the masses of both stars from an IMF

distribution of the type given by (2). The result of such pairing yields ~ 85 per cent of white dwarf - M dwarf systems, in disagreement with the study of Holberg (2009) which gives an upper limit of ~ 40 per cent (see section (2.2)). Such a distribution would also give a peak in the mass ratio distribution near $q = 0.2$ and a very steep decline toward $q = 1$, which is in disagreement with the observed, flat behaviour for $0.1 \lesssim q \lesssim 1$ discussed in section 2.1. We show the results in Fig. 3. In this figure we also show the predicted distribution of secondary star masses (centre panel) and M-dwarfs (right-end panel). We note that the peak of the M dwarf distribution is near spectral class M6, while the SDSS peak of the M dwarf distribution is near M3-M4. We also note that if both primaries and their companions are selected randomly from the IMF, then the outcome would be a small percentage of Sirius-type systems (~ 15 per cent) and double white dwarfs (~ 2 per cent).

We have also explored a distribution as given in (3). Here, the type of companion depends on the mass of the primary. The behaviour of $f_{obs}(q)$ and M_s can exhibit peaks at different locations and widths depending on the values assigned to k and σ. If we set $\sigma = 0.4$ and $k = 0.5$ we obtain a low percentage (~ 20 per cent) of white dwarfs - M dwarf systems and a high percentage of Sirius-type and double white dwarf systems of 57 and 23 per cent respectively. Fig. 4 shows the results for this set of values. We also note that the peak of the M dwarf distribution for the companions is predicted to occur around M3-M4, as observed. However the slope of the mass ratio distribution for $q \gtrsim 0.1 - 0.2$ is again too steep to fit the observational evidence pointing to a flat $f_{obs}(q)$.

In the pairing cases considered above, the masses of the two stars have been drawn from some mass distributions which yields binaries with a certain observed mass ratio distribution. What we are going to look at now, is the situation where the physical processes leading to binary star formation establish the distribution of the primary mass *and* of the mass ratio distribution $f(q)$ (the "generating mass ratio" distribution). This approach on generating binaries could be interpreted in the framework of the scale-free fragmentation scenario for binary formation of Clarke (1996) who considered a collapsing and breaking up gas cloud whose final fragments are clumps of mass of M_{clump} which are distributed according to a mass function $F_{clump}(M_{clump})$. In her model, each clump then divides into two pieces whose mass ratio distribution is $f(q)$. That is, the fraction of clumps with mass ratio in the range q to $q + dq$ is $f(q)dq$. In her studies, the function $f(q)$ is independent of M_{clump}, which is the necessary assumption for scale-free cloud fragmentation.

In our calculations, we have considered a uniform mass ratio distribution $f(q)$ and a power-law for the primary mass distribution $f(M_p)$, as indicated by the SDSS data. It is important to note that the stellar mass limits play a crucial role in the determination of the *observed* mass ratio distribution $f_{obs}(q)$. In the studies of white dwarf binaries, however, the spectral type of the white dwarf's progenitor is restricted to be between F and late B which gives rise to the flat $f_{obs}(q)$ shown in Fig. (5). Such a pairing yields a small percentage of white dwarfs with M dwarf companions (~ 18 per cent) and a large percentage of Sirius-type systems (~ 47) and double white dwarfs (~ 35). The peak of the M dwarf distribution
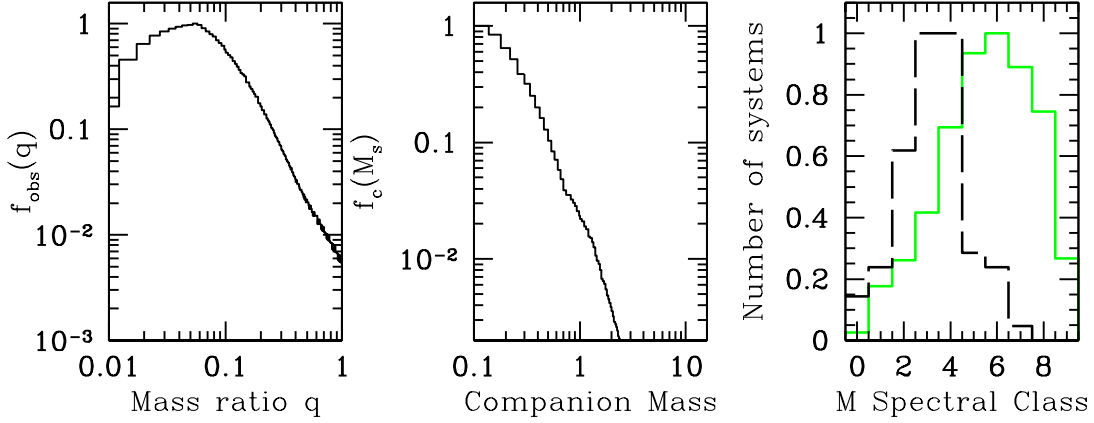
Figure 3. From left to right: Mass ratio distribution, companion mass distribution $f_c(M_s)$ and spectral class distribution of M dwarf companions for a pairing where the masses of the components are drawn from the IMF of the type (2). The panel on the right shows the normalised SDSS M dwarf distribution of wide white dwarf-M dwarf binaries (dashed line), while the solid line shows the model prediction for the distribution of M dwarfs.
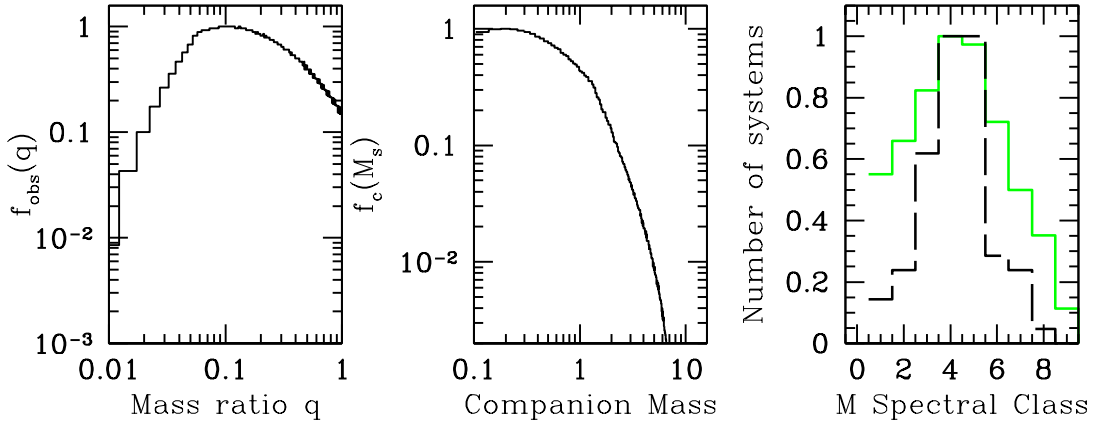

Figure 4. From left to right: Mass ratio distribution, companion mass distribution $f_c(M_s)$ and spectral class distribution of M dwarf companions for a pairing of the type (3) with $\sigma = 0.4$ and $k = 0.5$. The panel on the right shows the normalised SDSS M dwarf distribution of wide white dwarf-M dwarf binaries (dashed line), while the solid line shows the model prediction for the distribution of M dwarfs.

also falls near M4, which is in general agreement with the SDSS observations.

Finally, it may be of interest to address the fact that some observations show the existence of a "twin peak", caused by stars of similar masses pairing up. There have been some doubts on whether this peak is real, since binaries whose components have similar masses tend to be brighter than those with fainter companions, thus resulting into a possible oversampling of these systems (e.g. Halbwachs et al. (2003)). On the other hand, Tokovinin (2000) and Halbwachs et al. (2003) also report that the frequency of twins does seem to be higher at short orbital periods ($< 40 - 50$ days). They also note that the mass ratios of their visual binary sample with wide separations does not exhibit a peak around $q = 1$ (Halbwachs 1983).

The "twin peak" seems also to be common among massive primaries. Pinsonneault & Stanek (2006) report that systems with $M_2 > 0.95M_1$ comprise 45 per cent of their

population of massive binaries while the rest exhibits a flat mass ratio distribution.

Thus, it appears that the stellar components of binaries with short periods and some of the more massive binaries "prefer" similar mass companions. This implies the coexistence of different binary formation mechanisms.

One possibility is that in some cases, dictated by some as yet unknown initial conditions, the scale-free fragmentation of the cloud into clumps is then followed by vigorous disc fragmentation (see section 4.1). As theoretically demonstrated by the hydro-dynamical calculations of Bate (1997), such disc fragmentation would create systems whose mass ratios approach unity. This behaviour can be modelled by setting $k = 1.0$ in equation (3). In this picture, scale-free fragmentation would then be followed by a formation process that is dependent on the mass of the primary star.

In Table 4.2 we summarise our results in terms of the various systems that are generated via the pairing mecha-
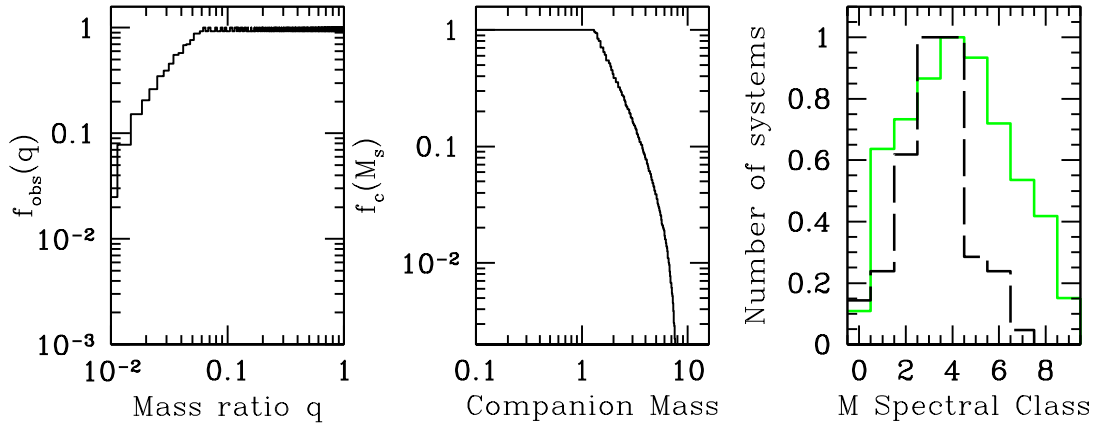
Figure 5. From left to right: Mass ratio distribution, companion mass distribution $f_c(M_s)$ and spectral class distribution of M dwarf companions for a pairing of the type (4) with $\beta = 0$. The panel on the right shows the normalised SDSS M dwarf distribution of wide white dwarf-M dwarf binaries (dashed line), while the solid line shows the model prediction for the distribution of M dwarfs.

nisms considered in this paper. This table gives a prediction of the relative percentages of systems that one should find in a complete volume limited sample of white dwarf binaries.

5 CONCLUSIONS

In this paper, we have seen that it is possible to gain some insights in the behaviour of the mass ratio distribution at low values of q by studying binary systems comprising of white dwarf primaries and main sequence companions. This has allowed us, via an initial-final mass relationship for white dwarfs, to draw some conclusions on the pairing properties of Main Sequence of spectral type F to late B, which are the progenitors of the currently observed white dwarfs. The constraints that we have used are (i) the white dwarfs - M dwarf wide binary sample from the SDSS (ii) the Holberg (2009) percentage of observed white dwarf binaries in the 20 pc local sample and (iii) the fact that the mass ratio distribution for Galactic binaries, ranging from G to early B-type stars and even for young protostellar associations, is either flat or slightly raising toward $q \sim 0.1 - 0.3$. The aim of this paper was to investigate whether it is possible, on the basis of the data currently at hand, to explore and possibly favour some of the proposed routes for star formation.

A prediction of our studies is the existence of a large fraction of "hidden" white dwarfs in binaries consisting of either double white dwarfs or close (unresolved) Sirius-like systems.

In this context, we would also like to note that using the ROSAT Wide Field Camera survey of the extreme ultraviolet, Burleigh, Barstow & Holberg (1998) have revealed the existence of a previously unidentified sample of hot white dwarfs in unresolved, detached binary systems. These stars are invisible at optical wavelengths due to the proximity of their much more luminous companions (spectral type K or earlier). However, for companions of spectral type A5 or later, the white dwarfs are easily visible at far-ultraviolet wavelengths, and can be identified in UV spectra. In total, 16 such systems have been discovered in this way through ROSAT, EUVE and IUE observations. Further observations

of this kind should reveal how common these systems really are.

Clearly, also a much larger sample of white dwarf - M dwarf companions is needed to further explore the incidence of such systems. At the moment, the number is still too small and uncorrected for observational biases. A clean, enlarged sample of this type is crucial to shed more light on how binaries are formed and thus on possible star formation mechanisms.

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Table 1. Prediction of the relative percentages of systems in a complete volume-limited sample of white dwarf binaries.

Pairing mechanism	Systems with M dwarfs (per cent)	Sirius-type systems (per cent)	Double white dwarf systems (per cent)
Random pairing with secondaries drawn from IMF	83	15	2
Secondaries drawn from Gaussian distribution ($\sigma = 0.4$, $k = 0.5$)	20	58	22
Flat generating mass ratio	18	47	35

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